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IMPROVEMENT OF ZIGBEE ROUTING PROTOCOL INCLUDING ENERGY AND DELAY CONSTRAINTS

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Abstract*: Besides energy constraint, wireless sensor networks should also be able to provide bounded communication delay when they are used to support real-time applications. In this paper, we propose an improvement of Zigbee routing protocol integrating both energy and delay constraints. By mathematical analysis and simulations, we have shown the efficiency of this improvement.*
Keywords: Real-time, wireless sensor network, routing, energy, delay, lifetime, delivery rate.

1. INTRODUCTION

With recent technical and technological advances in WSN (Wireless Sensor Network), it becomes now possible to envisage not only simple non real-time data collect but also more complicated real-time applications. Thus, WSN can be extended to include actuator nodes, called by some researchers wireless sensor and actuator network [1]. Each sensor node is composed of one or more sensors, a processor and a radio transmission unit. All of them are supplied by an unchangeable battery. Sensor nodes collect data from the environment that they are supervising and send them to other nodes or a base station (sink). This station processes received data and sends appropriate action commands to the actuators [2, 3]. Actuator nodes are assumed less energy constraint than the sensor nodes.

It is worth pointing out that the main research efforts in developing WSNs have focused on how to extend the network lifetime with respect to limited battery energy. However, when real-time applications are deployed on them, extending the lifetime of the network should be done without jeopardizing real-time communications from sensor nodes to other nodes or to data sinks. For example, a surveillance system needs to alert authorities of an intruder within a few seconds of detection [4]. Unfortunately, there is little work on the real-time communication support for WSNs.

For energy saving, most of work focuses on the communication protocol design since in a WSN the radio communication unit is the major power consumer in the node (it consumes about one thousand CPU units) [5]. IEEE 802.15.4 Task Group together with Zigbee Alliance [6] have developed an entire communication protocol stack for Low-Rate Personal Area Networks. One of the potential applications of this standard is in WSNs. This standard represents the new generation of distributed embedded systems for pervasive computing. IEEE 802.15.4 standard deals with the energy optimization in the physical layer and the Medium Access Control (MAC) sub-layer. Energy saving is mainly achieved by defining a sleeping period (inactive period) in a superframe. The Zigbee specifications define the routing and the application layer. The Zigbee routing protocol is almost the same as AODV (Ad hoc On-Demand Distance Vector) with the exception of route maintenance. Even one may agree that AODV can always choose the route that minimizes the delay (or equivalently the number of hops), it does not take into account energy optimization. In this paper, we aim at improving the Zigbee routing protocol by including both energy and delay considerations.

Several energy-aware metrics have been proposed [7, 8, 9] to optimize the energy consumption during the routing process. However they omit the real-time aspect. [10] presents a routing approach which optimizes the network lifetime for real-time applications. However, it does not take into account the link's reliability. It should be noted that a route that chooses an unreliable link may experience longer delay because of the higher retransmission probability, which will in turn increase the energy consumption. The Real-time Power-Aware Routing (RPAR) protocol [11] reduces communications delays by adapting the transmission power to the workload. However, it does not optimize the network lifetime.

So, in this paper, we will focus on maximizing the sensor network lifetime while still taking into account the delay requirement of real-time communications. Our main idea is to find a new routing metric which is capable of including delay, energy, as well as link reliability factors. In our study, we used IEEE 802.15.4 protocol and Zigbee AODV. We are going to optimize the network lifetime under the delay constraint at the routing layer. Without loss of generality, the delay of a route is considered equivalent to the number of hops on the route and we assume that one can find the limit on the hop number for a given real-time communication constraint.

The rest of this paper is organized as follows. In Section 2 provides a mathematical analysis for packet forwarding. We will give a routing metric that trades off between maximizing the sensor network lifetime and satisfying the communication delay. By simulations, we will compare the performance of our

routing approach with the existing ones in Section 3. Finally, Section 4 gives conclusions and describes future directions.

2. PROPOSED ROUTING METRIC

2.1 Model

In this study, we adopt the model defined in [7]. This model captures the packet reception rate (PRR) between two nodes as follows. Nodes have full connectivity if they have a distance less than D_1. They are disconnected if they are separated by a distance greater than D_2. The expected PRR decreases smoothly in the transitive region between D_1 and D_2. The behavior is modeled by (1)

$$PRR = \begin{cases} 1 & d<D_1 \\ \left[\dfrac{D_2 - d}{D_2 - D_1} + X \right]_0^1 & D_1 \le d \le D_2 \\ 0 & d > D_2 \end{cases} \quad (1)$$

where $[.]_a^b = max\{a, min\{b, .\}\}$ and $X \sim N(0, \sigma^2)$ is a Gaussian variable with variance σ^2.

2.2 Metrics

The wireless sensor network is presented by a graph $G = (V, A)$, in which V is the set of nodes including the base station. The set of edges $A \subset V \times V$ such that $(i, j) \in A$ if nodes i and j can transmit to each other. To optimize the routing path, we assign each node the remaining energy and each vertex the delivery rate.

In the following, we are interested in the metric of the path efficiency. This metric considers the path energy efficiency and the delay experienced along this path. Here we are going to maximize energy efficiency while minimizing the delay together. Thus, we first define this path efficiency, E, to be the ratio of the path energy efficiency, E_{eff}, to the delay required to transmit a packet from the source to the destination. The energy efficiency represents a trade-off between delivery rate and energy consumption along this path. In order to maximize the path efficiency and minimize the energy consumption, the energy efficiency is quantified as the ratio of the delivery rate, E_r, to the total energy consumed to transfer the packet to the destination node E_e. Thus, this energy efficiency is expressible by

$$E_{eff} = \frac{E_r}{E_e} \quad (2)$$

[1] This equation is modified, in numerator, $d - D_1$ is replaced by $D_2 - d$ to find 1 when $d = D_1$.

The end-to-end delivery rate for a path φ takes into account the delivery rate of each link in this path. So, this end-to-end delivery rate is the product of packet reception rate of each link in φ as shown by

$$E_r = \prod_{k \in \varphi, k \neq destination} prr_{k,k+1} \quad (3)$$

where $prr_{k,k+1}$ is the packet reception rate between node k and its forwarder $k+1$ as shown in Figure 1.

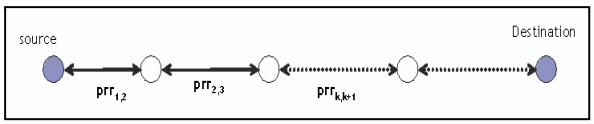


Fig. 1. Path

Taking into account the retransmission (R: number of allowed retransmission), the required energy for the packet delivery for the first transmission is calculated by

$$\hat{E}_e^1 = p_{i,i+1}(E_e^i + b) + a(b + \hat{E}_e^2) . \quad (4)$$

Using a recurrent calculation, the required energy for the packet delivery for the R^{th} retransmission is given by

$$\hat{E}_e^{R+1} = p_{i,i+1}(E_e^i + b) + ab . \quad (5)$$

Finally, the required energy for the packet delivery is

$$E_e = \frac{(prr_{i,i+1}(E_e^i + b) + ab)(1 - a^{R+1})}{1 - a} \quad (6)$$

where $prr_{i,i+1}$ is the packet reception rate for the forwarder i, E_e^i is its energy cost that refers to the energy consumption from the source to the node i. b is the packet processing energy (transmission and reception) and $a = 1 - prr_{i,i+1}$.

As we are using the IEEE 802.15.4, the number of allowed retransmission is fixed to 3. Therefore the required energy will be

$$E_e = \frac{(prr_{i,i+1}(E_e^i + b) + ab)(1 - a^4)}{1 - a}$$

If $prr_{i,i+1}=0$ (the link is broken), the consumed energy is equal to $(R+1)b$, in our case $4b$.
By replacing E_r and E_e in (2), the energy efficiency is given by

$$E_{eff} = \frac{\prod_{k \in \varphi, k \neq destination} prr_{k,k+1}}{(prr_{i,i+1}(E_e^i + b) + ab)(1 - a^4)} (1 - a) \quad (7)$$

As the routing approach has to respect the delay to guarantee the "deadline" for real-time communications, the path efficiency could further be represented by $E = E_{eff}/delay$.

$$E = \frac{\prod_{k \in \varphi, k \neq destination} prr_{k,k+1}}{delay(prr_{i,i+1}(E_e^i + b) + ab)(1 - a^4)}(1-a) \quad (8)$$

The routing approach presented by Coleri [10] guarantees the delay performance too. However, the corresponding delay is not included in the routing metric. In fact, in this approach only paths that offer delay less than the allowed delay are considered in the routing choice. Furthermore, the time is divided into time frames and at the beginning of each frame, the base station floods the network with a tree construction packet. Thus, there is significant energy consumption in the routing process. However, we use the AODV routing protocol with a modified routing metric as shown in (8). Hence, the route is setup according to the AODV request/response cycle. The delays are collected by route response message. Consequently, we have not increased the network load.

However, considering only the consumed energy is not sufficient to maximize the lifetime of the sensor network. We must include the remaining energy in the routing metric to balance the load of the network. Thus the path efficiency $E_l$is given by

$$E_l = E \cdot e_i \quad (9)$$

where e_i is the remaining energy of the forwarding node i.

The new metric for the path efficiency which includes the delay, the path reliability and the lifetime efficiency, E_l, can be calculated from

$$E_l = \frac{\prod_{k \in \varphi, k \neq destination} prr_{k,k+1}}{delay(prr_{i,i+1}(E_e^i + b) + ab)(1 - a^4)}(1-a) \cdot e_i \quad (10)$$

Once we have defined our routing metric, we included it in the AODV routing protocol. Thus, our new version of AODV chooses the most efficient path to the destination node by considering both energy and delay constraints.

3. SIMULATION RESULTS AND DISCUSSION

In this section, the performance of the proposed routing metric is evaluated and compared with AODV routing protocol and Coleri routing metric. Furthermore, we use NS-2 simulators to implement the physical and MAC layers of IEEE 802.15.4. We have changed the existing implementation in NS-2 of AODV to integrate our metric. Thus, we have a new version of AODV, which we call Enhanced AODV.

The primary purpose of our simulation is to observe the network lifetime resulted by our routing optimization. Moreover, we consider the delivery rate as another performance metric.

The simulated networks consist of 11, 22 and 101 nodes respectively.

3.1 Assumptions

The following assumptions are made in this study.

1. We consider a wireless sensor network that consists of a base station and several sensor nodes. These sensor nodes generate data for transfer to the base station. Delay constraint is only imposed on this sensor to base station communication.
2. Sensor nodes have a low mobility that is the case for most of the sensor network applications.
3. The delay needed to transmit a packet from a source node to a destination node is equivalent to the number of hops counted between these two nodes.
4. The operational lifetime of the sensor network is defined as the time until the first 5% of nodes died as proved in [10].

3.2 Lifetime

We study here the sensor network lifetime. We observe in Figure 2 that at the beginning the three routing approaches have the same result. In fact, in the beginning of the network life, all nodes have a maximal amount of energy. Thus, the three routing approaches will have the same routing choices. Once the sensor energy decreases, the difference between these routing approaches appears. We observe that the Enhanced AODV routing approach let sensors be alive for a longer time than AODV routing protocol does.

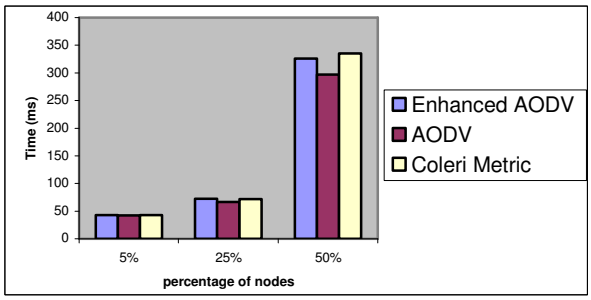


Fig. 2 Comparison of the time at which a specific percentage of the nodes are dead between Enhanced AODV, AODV and Coleri metric .

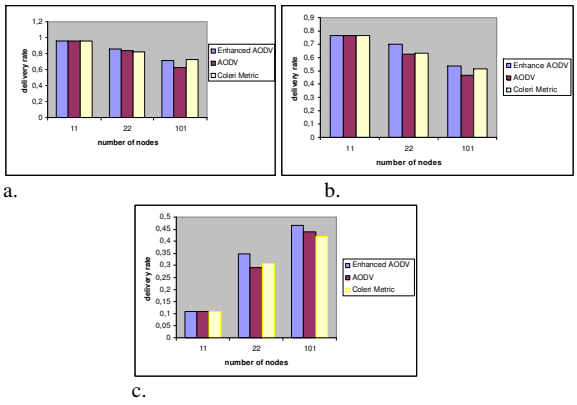
Moreover, both of Enhanced AODV and Coleri routing metric give almost the same time for the death of a specific percentage of nodes. This is an

expected result since both routing metrics aim to maximize sensor network lifetime.

3.3 Delivery rate

In this sub-section, we focus on the optimization of the network delivery rate. We define the network delivery rate as the ratio of the total received packets to the total sent packets in the sensor network. We compute this delivery rate at different times in the sensor network lifetime and compare the results among Enhanced AODV, AODV and Coleri metric.

Figure 3 a. gives the delivery rate before the death of 5% of nodes. We notice that for a sensor network of a small number of nodes, all of the studied routing approaches offer the same delivery rate. In fact, in small sensor network there is almost one path from the source to destination. Thus, all of the routing algorithms choose the same path. However, for a network with a larger number of nodes, the Enhanced AODV performs better than AODV does. Moreover, the Enhanced AODV and Coleri routing metric gives almost the same delivery rate.



a. b.

c.

Fig. 3 a. Delivery rate before the death of 5% of nodes. b. Delivery rate before the death of 25% of nodes. c. Delivery rate before the death of 50% of nodes

Figure 3 b. shows the delivery rate before the death of 25% of nodes. In the same way as mentioned before, for a small sensor networks, all of the studied routing approaches give the same delivery rate. However, the benefit due to the optimization of delivery rate by the Enhanced AODV is clear. In fact, these routing approaches give better delivery rate than AOV and Coleri metric. Thus, although the Enhanced AODV and the Coleri metric offer the same network lifetime, the former gives a better delivery rate.

From the results given by the Figure 3 c. we notice that the Enhanced AODV offers better delivery rate than AODV and Coleri routing approaches. Thus, for different moment of the network lifetime, the delivery rate is always better with the Enhanced AODV routing approach.

4. CONCLUSION

A successful deployment of real-time applications over WSNs needs to satisfy the required timing properties under energy consumption constraints. As Zigbee routing protocol does not address energy and delay issues together at the same time, we propose in this paper a new routing metric. The benefit of this metric has been shown by simulations when embedded into AODV protocol. Moreover, we started implementing this metric in MecaZ. As a future work, we plan to test this metric in a real WSN.

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